SPACE NUCLEAR SYSTEM

EXPANSION JOINTS

SUMMARY REPORT

AEC Research and Development Report

Atomics International Division
Rockwell International

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EXPANSION JOINTS

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FOREWORD

The work described here was done at the Atomics International Division of Rockwell International Corporation, under the direction of the Space Nuclear Systems Division, a joint AEC-NASA office. Project management was provided by NASA-Lewis Research Center and the AEC-SNAP Project Office.

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ABSTRACT

The engineering, design, and fabrication status of the expansion joint unit (EJU) to be employed in the NaK primary coolant piping loop of the 5-kwe Reactor Thermoelectric System are described. Four EJU's are needed in the NaK primary coolant piping loop. The four EJU's, which will be identical, utilize bellows as the flexing member, are hermetically sealed, and provide double containment. The bellows are of a nested-formed design, and are to be constructed of 1-ply thickness of 0.010-in. Inconel 718. The EJU's provide a minimum piping load margin of safety of +0.22.
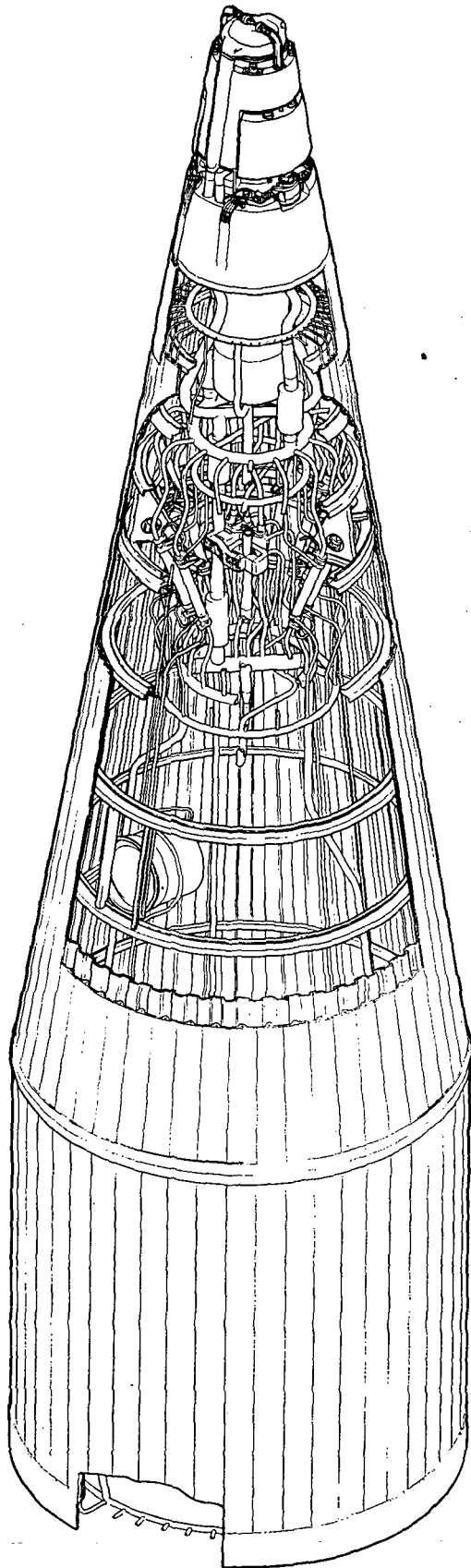
Figure 1. 5-kwe Reactor Thermoelectric System

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I. INTRODUCTION

A series of compact nuclear reactors and electrical power systems were designed, developed and tested for the Systems for Nuclear Auxiliary Power (SNAP) program. The ZrH reactors for these systems were fueled by hydrided zirconium-uranium rods enclosed within high-temperature corrosion-resistant tubes. Windows in the external beryllium neutron reflector were adjusted by rotating drums or sliding segments to regulate neutron loss from the core and, thus, the power output of the reactor. A direct radiating thermo-electric module-powered power conversion system (PCS) produced over 500 w of electrical power on the flight-tested SNAP 10A system. Mercury-Rankine cycle turbogenerator PCS's of 3-kwe and 30-kwe power ratings were demonstrated for the SNAP 2 and SNAP 8 systems, respectively. The latest 5-kwe Reactor Thermoelectric System was based on the compact, tubular, thermoelectric PCS. The NaK used to transfer heat from the reactor to the PCS and then from the PCS to the space radiator was circulated by dc conduction-type electro-magnetic (EM) pumps on the thermoelectric system, and by mechanical centrifugal pumps on the Mercury-Rankine systems.

A. NEED FOR EXPANSION JOINTS

The complexity of the piping which carries the heat transfer NaK throughout the primary and secondary loops is illustrated in Figure 1. This piping is heated to different temperatures during the various operational phases, resulting in expansion or contraction with respect to the components and supporting structures. Double-containment bellows-type expansion joint units (EJU's) are utilized at optimum locations to accommodate these piping movements with minimum loading on such components as pumps, volume accumulator units, and headers for thermoelectric modules and space radiator. The engineering studies, design, and fabrication of the EJU are summarized in this report.

B. GENERAL REQUIREMENTS

The following general requirements for the EJU, specified for the 5-kwe Reactor Thermoelectric System, are applicable to all SNAP systems:

1) The EJU boundary loading reaction forces imparted to the system piping shall not cause the piping stresses to exceed allowable magnitudes.

2) EJU length and weight shall be minimized within the objectives of meeting piping loading and bellows stress limitations and EJU reliability goals. To maximize the EJU reliability, the design shall utilize double containment of the NaK within the EJU. The double containment concept for bellows components was conceived and developed for the SNAP 10A expansion compensator unit.[1] The secondary containment (secondary containment bellows) will prevent loss of the NaK coolant in the event of leakage or failure of the primary containment bellows, and allow continued uninterrupted operation of the system after such an occurrence.

3) The internal NaK flow-through passage of the EJU shall be smooth, and flow pressure drop through the EJU shall not exceed the flow pressure drop through an equivalent straight length of piping by more than 50%.

4) The material for the EJU detail parts shall be compatible with NaK, and shall be weldable to the Type 316 SS piping of the 5-kwe system.

5) The EJU shall be designed to operate for 5 years at the pressures and temperatures of the NaK coolant piping system, after being subjected to the acceptance test and system launch conditions.

6) Common design of the EJU shall be utilized for all applications of the system, if possible.

II. PRIOR SNAP EXPANSION JOINT UNIT EXPERIENCE

Expansion joint design and performance testing were conducted for the Mercury Rankine SNAP Program in 1963-64.[2,3]

Endurance testing of a hydroformed multi-ply bellows-type joint was conducted with hot NaK circulating through it. The exterior surface of the joint was exposed to a vacuum environment and was thermally shielded to maintain the joint surface temperature close to the internal NaK temperature. The expansion joint was compressed approximately 0.3 in. during this test; conditions were as follows:

Operating time (hr)	3550
NaK temperature (°F)	1220 ± 20
NaK flow rate (gpm)	~3
NaK pressure (psia)	16
External pressure (torr air)	~8 x 10⁻³

Post-test inspection revealed the expansion joint to be in excellent condition and free of leaks or external mechanical defects.

Metallurgical examination of a joint subjected to torsional loading gave no evidence of failure.

Test data of other hydraulic, thermal cycles, and shock, vibration and acceleration tests and post-test examination results indicated that expansion joints with adequate performance and reliability margins can be designed and fabricated.
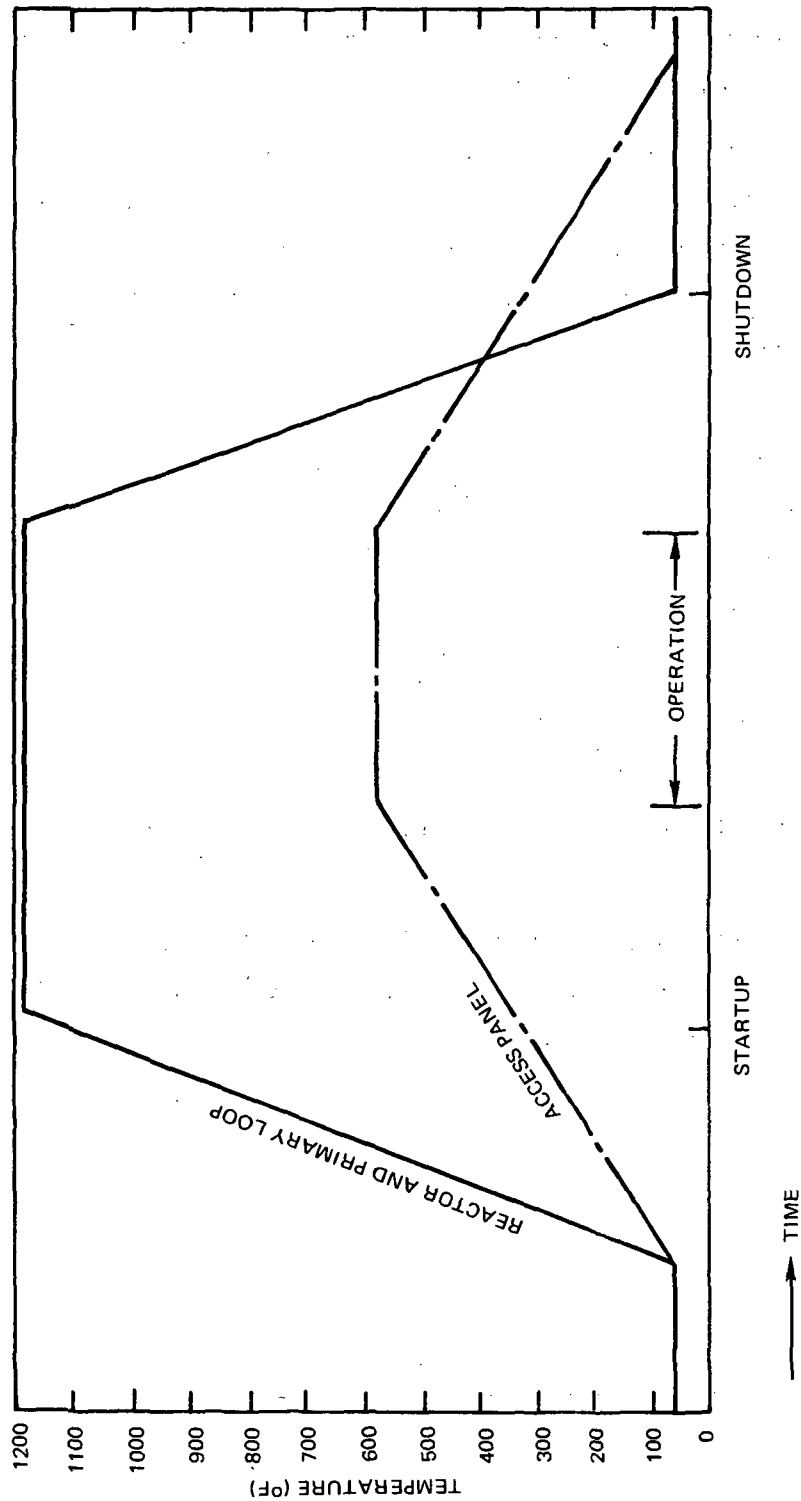
Figure 2. Typical Temperature Profiles During Reactor Thermal Cycle

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III. EXPANSION JOINT REQUIREMENT STUDIES

A. SYSTEM REQUIREMENTS

The 5-kwe piping system flexibility requirements and design selection trade study were based on the system conceptual design piping configuration. A typical component temperature profile is shown in Figure 2 for a reactor thermal cycle.

1. Primary Coolant Piping Loop

The calculated relative growth of the conceptual piping resulting from the heatup and cooldown from the initial room temperature stabilized conditions are shown on Table 1.

TABLE 1

PIPING THERMAL GROWTH IN CONCEPTUAL DESIGN PIPING

Location		At Startup (in.)	At Operation (in.)	At Shutdown (in.)
Primary Outlet Piping		0.589 Contraction	0.445 Contraction	0.144 Extension
Primary Return	Pump Outlet	0.499 Contraction	0.355 Contraction	0.144 Extension
	Pump Inlet	0.110 Contraction	0.110 Contraction	0.00

2. Secondary Coolant Piping Loop

The coefficients of thermal expansion of the Lockalloy selected for the radiator and of the Type 316 SS piping are essentially identical. All components of the secondary coolant piping arrive at their design temperatures at essentially the same time, and the greatest average temperature difference between any two adjoining pipes is 50°F. Consequently, the greatest relative thermal growth which will occur is 0.07 in. This relative thermal growth can easily be accommodated by required bends in the ~175-in. length of piping. Thus, the differential-thermal growth of the secondary piping can be absorbed without the use of any special loops, bends, expansion joint units, or other devices.

B. TRADE STUDIES FOR THE PRIMARY COOLANT PIPING LOOP

Five alternatives for solving the relative thermal growth problem of the primary coolant piping loop were studied. The pipe design used for the study was of minimum functional length. Without any thermal growth compensation devices, the maximum calculated piping stress was 98,000 psi, approximately four times the allowable stress of 25,200 psi.

1. Spring-Mounted Support

One method of reducing the piping stresses arising from the relative thermal growth is to decrease the spring rate (stiffness) of the piping support structure. If the stiffness of the support structure were reduced, part of the relative thermal growth would be relieved by the support structure flexibility. Reducing the stiffness of the support structure, however, introduces two other problems. First, the flexible support structure must be rigidly attached during the launch phase, and released prior to system startup. Mechanisms to accomplish this unlocking by remote signal introduce additional malfunction probability and associated loss of system reliability. The second problem is the imposition of support loading and relative thermal growth into the secondary piping loop from the primary piping loop. Consequently, the disadvantages of the flexible support system outweigh its advantage of stress reduction.

2. Piping Expansion Loops Using Type 316 SS Piping Material

A piping concept with a full pipe jog across the full width of the 5-kwe system and back was analyzed. The jog reduced the stress level to 25,800 psi, slightly above the allowable stress. A piping concept with two, 360-degree circular loops was also analyzed, with a resulting stress level of 25,600 psi.

Either the jog or the loops would require 24 in. axial increase of the 5-kwe support structure. The resulting design complexity, increased volume accumulator size, and increased shell and shielding weight associated with the greater length of piping and structure were determined to be excessive penalties to pay for the marginal design advantage.

3. Use of Piping Materials Other Than Type 316 SS

Use of piping material with a lower coefficient of thermal expansion than Type 316 SS would result in a reduction of the relative thermal growth. Materials

investigation indicated Hastelloy N as the only acceptable alternate. To operate at acceptable stress levels, however, two, 360-degree circular loops would be required, resulting in no design advantage over Type 316 SS.

4. Preheated Access Panel

Preheating the access panel to 1200°F prior to reactor startup would reduce the relative thermal growth and the resulting stresses. This design alternative would reduce the stresses to acceptable levels for either Type 316 SS or Hastelloy N piping. The separate system required for preheating would, however, significantly reduce system beginning-of-life reliability.

5. Expansion Joint Units

The fifth alternative was to provide an axially flexible device to absorb the relative growth while limiting the piping stresses and reactions on the components. Such an EJU with double containment bellows as the flexible member minimizes the total piping length, reducing the NaK inventory and also volume compensation requirements. The reduced piping stresses (minimum design margin of 0.22) allow the use of Type 316 SS, with its well known properties, for the piping. The EJU can be designed with large design margins (0.60 minimum), which, coupled with the design margin of the piping, result in high system reliability.

C. CONCLUSIONS FROM THE TRADE STUDIES FOR THE PRIMARY COOLANT PIPING LOOP

A conceptual system primary loop piping design utilizing four conceptual EJU's was selected on the basis of the following trade study conclusions:

1) Minimum length of piping necessary to carry the NaK fluid to the functional components in the system. The resulting simple piping design minimizes the length and weight of supporting shell structure and of the piping.

2) Minimum amount of NaK fluid in the system minimizes volume accumulator capacity requirement.

3) The above minimum length of supporting shell minimizes nuclear radiation shielding requirements.

4) The reduced stress permits the use of Type 316 SS for the piping. Type 316 is one of the most ductile and most highly reliable materials available for high temperature liquid metal piping applications.

5) The reduced reaction loads reduce pipe attachment structure and thermoelectric converter module load requirements. The reaction loads on the thermoelectric modules are expected to be well within their inherent capacity.

6) The single-ply nested-formed bellows applicable to the EJU require only one longitudinal weld and the minimum number of circumferential welds, all easily inspectable. This feature, coupled with the double containment provided by the primary and secondary bellows, results in very high NaK containment reliability.

7) The EJU design can be modified to accommodate changes in imposed loads and deflections. Additional convolutions can be added to the bellows assembly without any attendant changes in the overall piping and support structure design. Revisions in the imposed loads and deflection are expected as the system design is finalized.

IV. PROTOTYPE EXPANSION JOINT UNIT

A. DESIGN DESCRIPTION

1. Design Approach

The prototype EJU was designed to be installed in any of four locations of the 5-kwe Reactor Thermoelectric System primary coolant loop piping, as shown in Figure 3. The prototype EJU, shown in Figure 4, replaces a short section of the piping between rigid piping mountings to allow essentially free axial movement of the two pipe ends within the EJU. Hydroformed metal bellows provide a flexible closure between these pipe ends. The bellows spring rate, deflection, and the hydraulic imbalance determine the end reaction and the stress levels throughout the piping loop. The bellows in contact with the loop NaK are defined as primary containment bellows. A second bellows, defined as the NaK secondary containment bellows, serves as a backup containment barrier in the event of NaK leakage through the primary containment bellows. These bellows are identical and placed in tandem to minimize the perturbation of the straight-through NaK flow.

Design trade studies on bellows type, bellows material choice, number of bellows plies, and bellows material thickness were conducted and the nested-formed type bellows with a single ply of Inconel 718 was recommended.

A 50°F design margin was added to the expected piping temperature in calculating the relative growth of the system piping under various 5-kwe system operating modes.

2. Prototype EJU Performance and Design Requirements

The performance requirements for the prototype 5-kwe system for the EJU are delineated in a component specification and summarized in Table 2.

The following design requirements were also imposed:

1) EJU Materials. The bellows material shall be Inconel 718 per AMS 5596; all other parts shall be Type 316 SS.

REACTOR RETURN PIPING

REACTOR OUTLET PIPING

EJU NO. 1 LOCATION

EJU NO. 1 LOCATION

EJU NO. 2 LOCATION PUMP OUTLET

PUMP

EJU NO. 3 LOCATION PUMP INLET
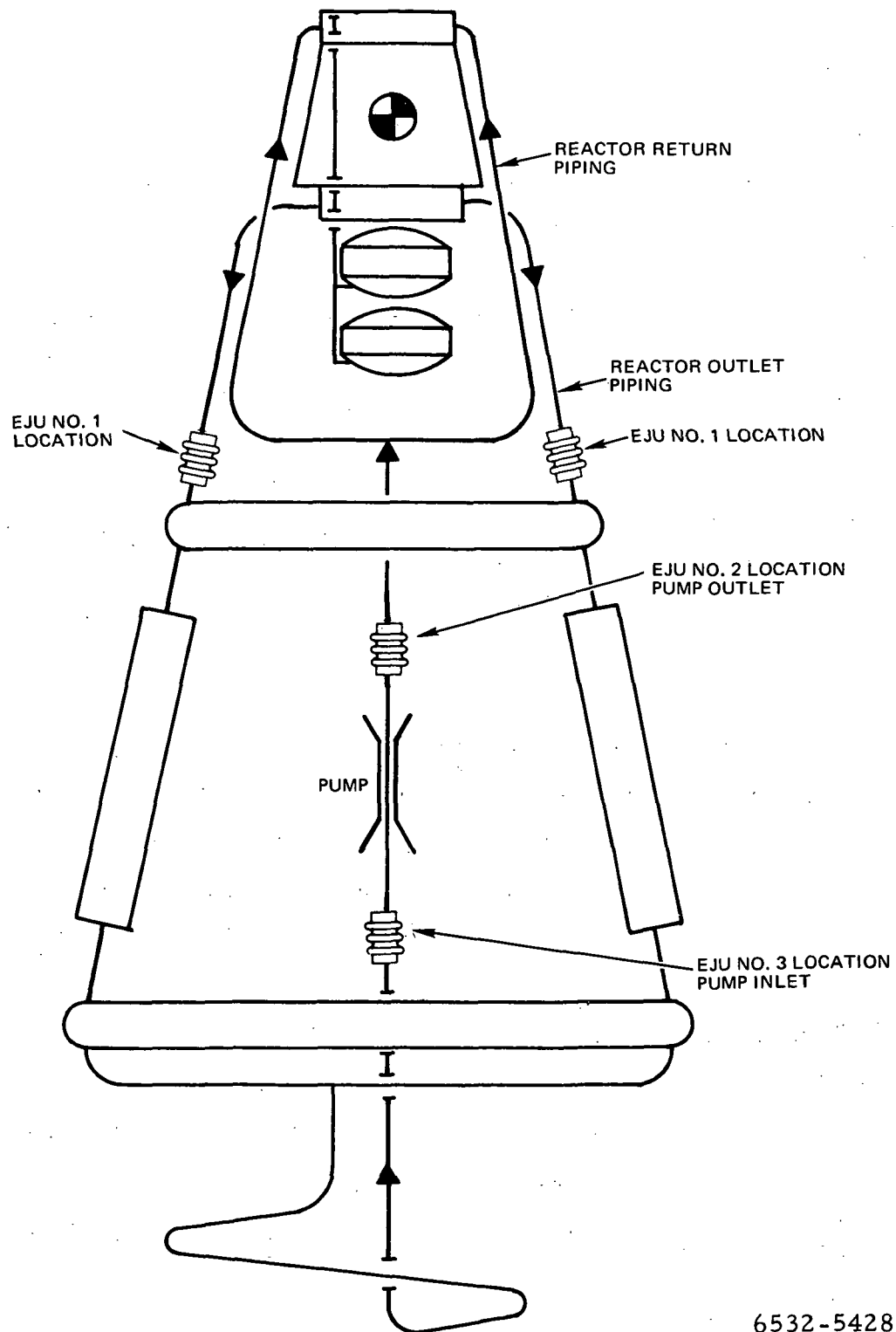
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Figure 3. Expansion Joint Unit Locations for the 5-kwe Reactor Thermoelectric System
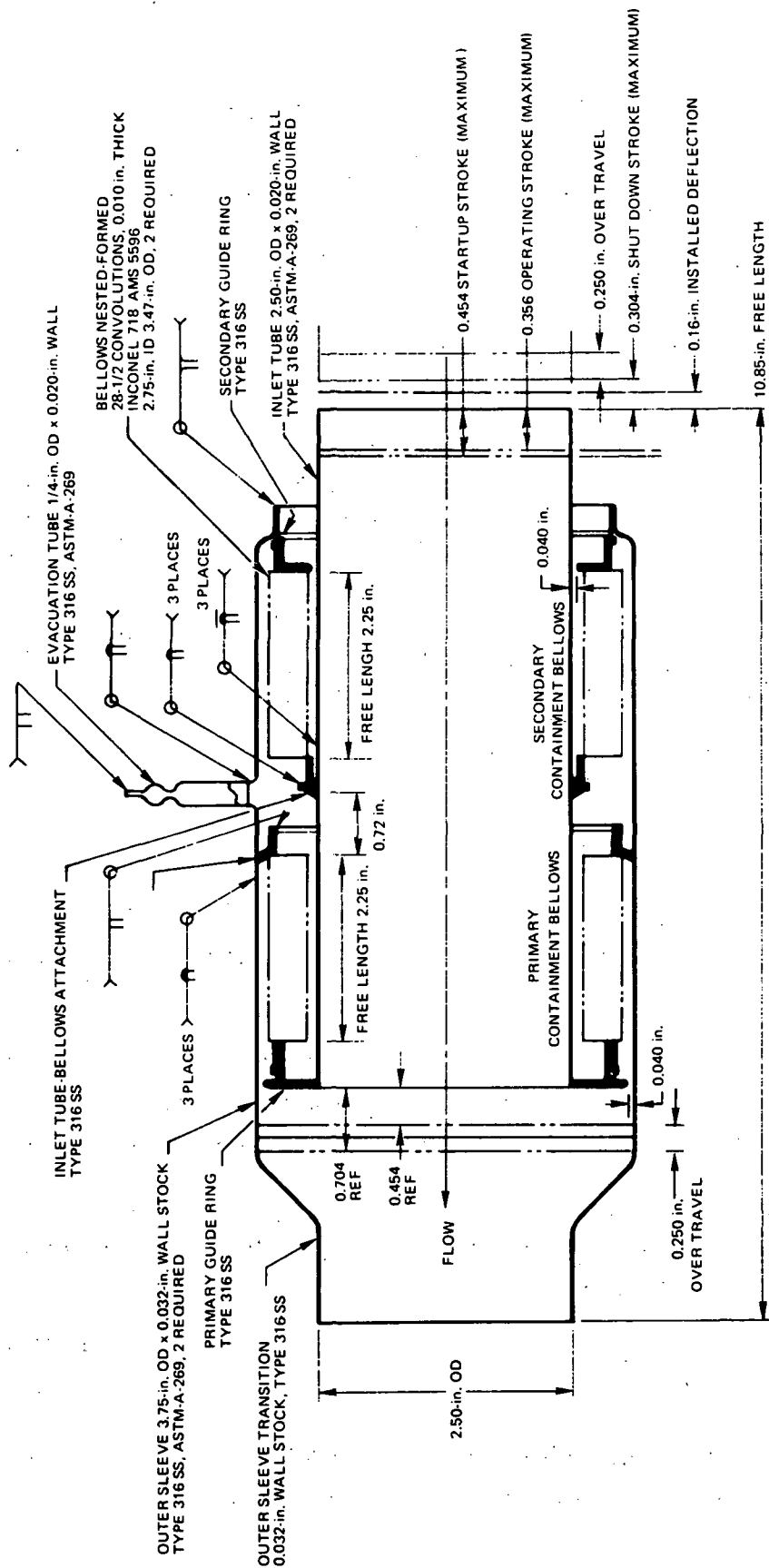
Figure 4. Prototype Expansion Joint Unit Design

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TABLE 2

EJU PERFORMANCE REQUIREMENTS

Operational Phase	Condition				
	Maximum NaK Temperature (°F)	Maximum NaK Pressure (psia)	Minimum EJU End Deflection* (in.)	Minimum EJU Offset (in.)	Maximum Axial† Load (lb)
Launch	70	46.1	0	±0.040	-
Startup Operation	1235	36.0	0.864 Contraction	±0.040	<|223|
Long-Term Operation	1300	32.0	0.766 Contraction	±0.040	<|223|
Reactor Shut Down	70	4.0	0.394 Extension	±0.040	<|223|

*Change in EJU length from initial installed length includes 0.250 in. over travel margin.
†End reaction force generated by the EJU.

2) <u>Bellows Stress.</u> The design stress of the bellows, under the startup condition, shall not exceed two-thirds of the minimum specified material yield strength.

3) <u>Proof Pressure.</u> When held at its free length, the EJU shall withstand an internal pressure of 10^{-3} torr to 55 psig (with respect to test environment) with no permanent distortion or material yielding.

4) <u>Burst Pressure.</u> When held at its free length, the EJU shall withstand an internal pressure of 92 psig without rupture of, or leakage through, the primary containment.

5) <u>Buckling Pressure.</u> Instability buckling of bellows shall not occur at an internal pressure of less than 70 psig.

6) <u>Bellows Natural Frequency.</u> The natural frequency of the bellows, without any damping, shall be greater than 35 Hz.

3. Description of EJU

The description and function of the major parts of the EJU, depicted in Figure 4, are presented in the following paragraphs.

a. Primary Containment Bellows

The primary containment bellows is welded at one end to the inner tube and at the other end to the outer tube, forming a flexible primary NaK containment unit. It is a relatively new type of hydroformed bellows called a nested-formed bellows which combines the low spring rate, large deflection characteristics of the welded washer type, while retaining the minimal length of welds of hydroformed bellows. The selected bellows has 28-1/2 single-ply convolutions of Inconel 718 material. External pressurization of the bellows with NaK precludes the bellows tendency to squirm.

b. Secondary Containment Bellows

The secondary containment bellows is identical in design to the primary containment bellows, and operates in tandem with it. Its attachment to the outer and inner tube sections of the EJU is almost identical to that of the primary containment bellows. The cavity between the two bellows, called the secondary volume, is evacuated and sealed. The main function of the secondary containment bellows is to provide a backup containment barrier to contain NaK leakage in the event the primary containment bellows leaks or fails. In the event of primary containment bellows leakage, the secondary containment bellows will also be pressurized externally.

As the secondary containment bellows is forced to stroke with the primary containment bellows, the spring rate forces of the two bellows are additive. The force from the two spring rates, plus the force of the NaK pressure acting on the bellows convolutions is the total force of the EJU on the adjacent piping and/ or component.

c. Outer Tube Section

The outer tube section is an expanded section of the loop piping which supports one end of both bellows and provides containment for both the primary and secondary volumes of the EJU.

d. **Inner Tube Section**

The inner tube section is also part of the loop piping and has the same functions as the outer tube section. It also serves as a smooth NaK flow liner through the greater length of the EJU.

e. **Bellows Mounting Ring**

The bellows mounting ring provides the support structure for attaching the bellows to the inner and outer tube sections. Two of the four rings required serve as structural stops for restricting the lateral off-set deflection (side deflection) to prevent the bellows convolutions from rubbing on the EJU inner and outer tube sections.

f. **Secondary Volume Evacuation Tube**

The evacuation tube provides access to the secondary volume for pressurization during testing and for evacuation and subsequent sealing by being pinched and welded.

B. **EJU PERFORMANCE**

The calculated performance of the EJU at each system location under the various 5-kwe system operational modes is shown in Table 3.

The factors listed in Table 3 are defined as follows:

End Deflection	=	Change in EJU length from initial installed length.
Bellows Deflection (δ)	=	Bellows compression (+) or extension (-) from EJU free length.
Bellows Spring Rate (K)	=	Combined spring rate of primary and secondary bellows at temperature noted.
Bellows Spring Force (Kδ)	=	Force required to compress the EJU from its free length.
Hydraulic Force	=	Force resulting from the internal NaK pressure action on differential area of bellows and piping.
Net Reaction Load	=	Bellows spring force and hydraulic force.

TABLE 3

PREDICTED EJU PERFORMANCE

System Condition	EJU Temperature (°F)	End Deflection (in.)	Bellows Deflection (in.)	Bellows Spring Rate (lb/in.)	Bellows Spring Force (lb/in.)	Internal NaK Pressure (psig)	Hydraulic Force (lb)	Net Reaction Load on Piping (lb)	Allowable Piping Load (lb)	Margin of Safety
Primary Outlet EJU										
Installation	70	0.0	-0.16	222	-35.5	0.0	0.0	-35.5*	-	-
Startup	1235	+0.614	+0.454	179	+81.3	36.0	101.0	182.3	223	+0.22
Operation	1300	+0.516	+0.356	176	+62.6	32.0	90.0	152.6	223	+0.46
Shutdown	70	-0.144	-0.304	222	-67.5	4.0	11.5	-56.0*	223	+3.0
Primary Return Piping										
Pump Outlet (Installation Deflection is -0.16 in.)										
Installation	70	0.0	-0.16	222	-35.5	0.0	0.0	-35.5*	-	-
Startup	1148	+0.541	+0.381	184	+70	36.0	101.0	171.0	262	+0.53
Operation	1205	+0.447	+0.287	181	+52	32.0	90.0	142.0	262	+0.85
Shutdown	70	-0.144	-0.304	222	-67.5	4.0	11.5	-56.0*	262	+3.7
Pump Inlet (Installation Deflection is 0.0 in.)										
Installation	70	0.0	0.0	222	0.0	0.0	0.0	0.0	-	-
Startup	1148	+0.12	+0.12	184	+22.1	36.0	101.0	122.1	~200	+0.64
Operation	1205	+0.13	+0.13	181	+23.5	32.0	90.0	113.5	~200	+0.76
Shutdown	70	0.0	0.0	222	0.0	4.0	11.5	11.5	~200	+16.5

*(-) Denotes tension forces imposed on piping.

Allowable Piping Load = Maximum compression (+) or tensile load (-) on piping to limit piping stress within allowable values.

$$\text{Margin of Safety} = \frac{\text{Allowable Load - Actual Load}}{\text{Actual Load}}$$

C. FABRICATION PLANS

Prior to closeout of the 5-kwe Reactor Thermoelectric System Program, plans were being formalized for the fabrication of six prototype expansion joint units. An AI specification which controls the materials, cleaning, welding, heat treatments, and quality assurance procedures for the fabrication of the nested-formed bellows was prepared. The fabrication of the EJU was to be conducted by outside sources in accordance with the AI specification and other controlling documents. In addition to the in-process quality assurance methods and steps specified in controlling documents, final acceptance inspections were planned.

D. VERIFICATION TEST PLANS

1. Objectives and Expected Results

The objective of the tests was to verify EJU performance prior to use in a nuclear system test.

The expected results of the tests were: (1) to assure satisfactory manufacturing process and quality control procedures, (2) to verify acceptable operating stress levels, and (3) to determine the bellows pressure-containment integrity and bellows fatigue cycle life, thereby demonstrating the inherent performance reliability in the nuclear tests. Endurance tests were expected to demonstrate the ability of the bellows to contain the hot NaK fluid under stress, and verify that the EJU would meet the requirements of the operating system.

2. Test Description

a. Acceptance Tests on all EJU's

The EJU acceptance tests would include helium leak check, dimensional verification, and verification that all of the requirements of the bellows fabrication specification and other controlling documents were met.

b. Nondestructive Tests of all EJU's

Nondestructive tests would be performed to verify that the EJU stroke, spring rate and flow-through pressure drop requirements were met.

Proof pressure tests would be performed to verify pressure-containment integrity design margin. Heat treatment material sample tensile tests would be performed at room temperature and at elevated temperature to verify material strength properties and to verify that proper furnace atmosphere was maintained during EJU heat treatment.

c. Fatigue Cycle Tests on Four EJU's

Short-term, accelerated fatigue tests would be performed at elevated temperature with a constant internal gas pressure of 36 psia. The EJU would be stroked the full allowable stroke within the limits of the EJU geometry. The fatigue cycle test would be stopped every 35,000 fatigue cycles to run a pressure/thermal cycle. The pressure would be cycled from the test operating pressure to zero and back to operating pressure, while the temperature is cycled from the operating temperature to room temperature and back to operating temperature.

d. Endurance Tests on Two EJU's

Endurance tests at the EJU maximum operating pressure, temperature, and stroke would be conducted in NaK at constant pressure and temperature with approximately one full-stroke fatigue cycle per day.

e. Post-Test Metallographic Examination

Failed EJU's would be given a metallographic examination, and the results released in a technical report. Based on the test and post-test examination results, EJU design improvements would be recommended.

V. SUMMARY

On the basis of trade studies, EJU's were selected as the method to compensate for the differential thermal growth which occurs between the NaK primary coolant piping and piping mounting structure of the 5-kwe Reactor Thermoelectric System. Four EJU's are required in the primary coolant piping loop. (None are needed in the secondary coolant piping loop.) The four EJU's — which will be identical — utilize bellows as the flexing members, are hermetically sealed, and provide double containment of the coolant loop NaK. The bellows are of a nested-formed design, and are to be constructed of one-ply thickness of 0.010-in. Inconel 718. The EJU's provide a minimum piping load margin of safety of +0.22. Plans for fabrication of six EJU's were being formulated at the time of the closeout of the program. Test plans to verify EJU performance have been formulated.

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